Charm lifetime[*]

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Abstract

A review of the charmed meson and baryon lifetimes is presented. Our knowledge of charmed particle lifetimes has greatly improved over the past two years, a crucial rôle having been played by the E687 experiment at Fermilab, which has almost quadrupled the samples of D mesons. The lifetime ratios $\tau(D^+)/\tau(D^0)$ and $\tau(D_s^+)/\tau(D^0)$ are now known with an accuracy of 1.7% and 3.7% respectively. In the baryon sector the statistics is still limited, but the experimental results on Λ_c^+, Ξ_c^0 and Ξ_c^+ exhibit a clear pattern of lifetime hierarchy, as expected from simple theoretical arguments. The first measurement of $\tau(\Omega_c^0)$ from E687 is also presented to complete the charmed baryon lifetime picture. The more accurate experimental scenario can provide information on non-perturbative QCD effects and the hadronic matrix elements.

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1 The issue of charm lifetimes

Heavy flavour hadrons consist of a heavy quark Q and a cloud of light quarks and gluons. Since the early days of QCD it has been known that, in the limit of infinite mass m_Q, the total decay rates and lifetimes of weakly decaying particles containing the same flavour Q should be identical and equal to that of a "free" heavy decay, the effect of the bound state being neglected in calculating the decay probability. This naïve intuition is contradicted by the experimental measurements of the charm family lifetimes, which manifest wide disparity between mesons and baryons (roughly a factor of 10 between Ξ_c^0 and D^+) and a significant difference between D^+ and D^0 (roughly a factor of 2).

This picture indicates that preasymptotic corrections, due to interactions with soft degrees of freedom in the light cloud, cannot thus be disregarded at the charm-mass scale; the inclusion of bound-state effects generates non-perturbative power corrections in $1/m_c$. Moreover, the presently available precise measurements of the ratio $R = \tau(D^+)/\tau(D^0) = 2.547 \pm 0.043$ and of the inclusive branching ratios $D^+ \to eX = (17.2 \pm 1.9)\%$ (PDG94) and $D^0 \to eX = (6.97 \pm 0.18 \pm 0.30)\%$ (CLEO) lead to an estimate of almost equal semileptonic decay widths for the D^0 and D^+:

$$\frac{\Gamma(D^0 \to eX)}{\Gamma(D^+ \to eX)} = \frac{Br(D^0 \to eX)}{Br(D^+ \to eX)} \times \frac{\tau(D^+)}{\tau(D^0)} = 1.03 \pm 0.12,$$

revealing that the extra rate in the total decay widths has to be looked for in the hadronic sector and that QCD corrections have to be taken into account. It is worthwhile pointing out that the lifetime differences in charmed mesons should be understood at the level of two-body decays; recent results on Dalitz plot analyses indicate that the high-multiplicity decays are dominated by resonant substructures, the only exception being $D^+ \to K^-\pi^+\pi^+$, which, alone among the D decays already analyzed, cannot be described without a large three-body non-resonant component.

2 Theory versus experiment

Preasymptotic effects in the meson sector enter in the form of W-exchange and W-annihilation diagrams, correcting the naïve spectator scenario; additional con-

tributions come from Pauli interference of the decay quark and spectator quarks in the D^+ only, lengthening the lifetime of the D^+ with respect to the D^0. In contrast to the main spectator decay, the evaluation of both these effects requires a knowledge of the D wave function. W-exchange and annihilation are expected to be inhibited by helicity conservation although soft gluon emission would attenuate the suppression. Quantitative estimates of both gluon enhancement and non-spectator contributions are difficult and subject to uncertainty. Anyway, the inclusion of these effects can account for the experimentally observed hierarchy:

$$\tau(D^+) > \tau(D^0) \approx \tau(D_s^+).$$

The $D_s \to 3\pi$ decay represents a unique window to evaluate the annihilation rate. A Dalitz-plot analysis of this channel allows the separation of components that only proceed through annihilation: namely, the three-body non-resonant and, in the absence of hostile final-state interactions, the $\rho^0 \pi^+$ contributions.

Analogously, the baryon sector manifests preasymptotic effects in the form of quark interference and W-exchange. The essential difference from the meson case, however, lies in the fact that W-exchange among valence quarks of the baryon is neither helicity nor colour suppressed. Moreover, soft-gluon radiation, the crucial question in meson decays, is a mere correction to the pure valence-quark process. Baryons are thus an ideal laboratory for studying preasymptotic effects; they also offer the advantage of access to four states whose different quark structure implies different combinations of W-exchange and interference of different strengths. The relative size of these effects leads to different predictions [1]:

$$\tau(\Omega_c^0) \approx \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+), \qquad \tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) \approx \tau(\Xi_c^+)$$
$$\text{or} \qquad \tau(\Omega_c^0) \leq \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+).$$

The hierarchy-pattern ends are due to the absence of W-exchange for the Ξ_c^+ and to large positive interference among s quarks in the Ω_c^0. Previous analyses have recently been revisited and improved [2], concluding that the Ω_c^0 could be either the shortest or longest living among the weakly decaying baryons depending on the strength of the spin-spin interaction and the value of the D decay constant. An evaluation of the different effects can also be found in ref. [3].

In the meson sector the ratio $\tau(D^+)/\tau(D^0) = 2.547 \pm 0.043$ is measured to 1.7%; the destructive interference invoked between D^+ external and internal

spectator diagrams can account for this factor 2 difference. The D_s^+-D^0 lifetime ratio, $\tau(D_s^+)/\tau(D^0) = 1.125 \pm 0.042$, is also now measured to good accuracy (3.7%) and turns out to deviate from the predicted value of unity at the 3σ level, thus raising the question of whether theoretical estimates can accomodate this difference. Precise information on this ratio provides a sensitive gauge of the impact of weak annihilation in charm decays and of the weight of $SU(3)_f$ breaking.

In the baryon sector different hierarchy patterns are predicted; they reflect intimate features of hadronic structure and are to a large extent model independent; *i.e.*, they do not require a knowledge of the B baryon wave-function. Thus, fairly accurate measurements would permit disentangling and determining the individual spectator and non-spectator effects. Once established, the observed hierarchy would imply relations between hadronic matrix elements of the operators involved, unique information otherwise inaccessible. Unfortunately, in the baryon case we do not have the powerful tool of factorization (applicable to mesons). From this point of view, experimental information is necessary to probe our understanding of weak-decay dynamics at preasymptotic scales.

It should not be forgotten that the QCD-based inclusive approach will never become fully quantitative in the charmed family; the c-quark lies below or at the border of the domain where the heavy-mass expansion may be useful, which makes the task challenging. The enhanced rôle of preasymptotic effects leads to the necessity of carefully considering all operators to be included in the matrix elements: some updated analyses are now being produced [2, 4]. The theory issue then concerns the size of the lifetime differences and absolute lifetime predictions. The measurement of the doubly strange Ω_c^0 baryon lifetime has turned out to be crucial; here strong spin terms, as in the mesons, are present and the conjecture of an unknown mechanism (distinguishing between mesons and antitriplet baryons) somehow connected with the spin terms can be tested.

3   The experimental scenario

The experimental scenario is chronologically portrayed in tables I and II. The D meson statistics has been steadily increasing over the years with, basically, two milestones: the E691 and E687 fixed-target photoproduction experiments

Table I: D^+, D^0, D_s^+ lifetime measurements.

Meson	Experiment	Year	Beam, reaction	Events
D^+	E687	1993	γ Be, $D^+ \to K^-\pi^+\pi^+$	9189
	NA14	1990	γ, $D^+ \to K^-\pi^+\pi^+$	200
	ACCMOR	1990	π^- Cu 230 GeV	317
	ARGUS	1988	e^+e^- 10 GeV	363
	E691	1988	Photoproduction	2992
	LEBC-EHS	1987	π^-p and pp	149
	CLEO	1987	e^+e^- 10 GeV	247
D^0	E687	1993	γ Be, $D^0 \to K^-\pi^+, K^-3\pi$	16730
	NA14	1990	γ, $D^0 \to K^-\pi^+, K^-3\pi^-$	890
	ACCMOR	1990	π^- Cu 230 GeV	641
	ARGUS	1988	e^+e^- 10 GeV	776
	E691	1988	Photoproduction	4212
	LEBC-EHS	1987	π^-p and pp	145
	CLEO	1987	e^+e^- 10 GeV	317
D_s^+	E687	1993	γ Be, $D_s^+ \to \phi\pi^+$	900
	NA14	1990	γ, $D_s^+ \to \phi\pi^+$	15
	ACCMOR	1990	π^- Cu 230 GeV	54
	HRS	1989	e^+e^- 29 GeV	18
	ARGUS	1988	e^+e^- 10 GeV	144
	E691	1988	Photoproduction	228
	CLEO	1987	e^+e^- 10 GeV	141

at Fermilab. In the baryon field the statistics is still limited and measurements are affected by large errors, but data are now becoming available and we are also benefitting from the first result on Ω_c^0 lifetime from E687, completing the four-baryon scenario. At this conference a very preliminary estimate of $\tau(\Omega_c^0)$ from WA89 has been presented; a more reliable measurement will hopefully be available soon. The experimental scenario is dominated by E687, which alone has measured all the charmed hadron lifetimes; the results are thus checked as internally consistent and the relative ratios, characterizing the hierarchy patterns, are to a large extent unbiased by systematic effects. Details of the experiment can be found in ref. [5] and the general methodology applied in refs. [6]. In tables III and IV the Particle Data Group 1994 meson and baryon lifetimes are reported

Table II: Λ_c^+, Ξ_c^+, Ξ_c^0 and Ω_c^0 lifetime measurements.

Baryon	Experiment	Year	Beam, reaction	Events
Λ_c^+	E687	1993	γ Be, $\Lambda_c^+ \to pK^-\pi^+$	1340
	NA14	1990	γ, $\Lambda_c^+ \to pK^-\pi^+$	29
	ACCMOR	1989	$pK^-\pi^+$ + c.c.	101
	E691	1988	Photoproduction	97
	LEBC	1988	$\pi^- p$ and pp	9
Ξ_c^+	WA89	1994	Σ^- Cu-C, $\Xi_c^+ \to \Lambda K^-\pi^+\pi^+$	20
	E687	1993	γ Be, $\Xi_c^+ \to \Xi^-\pi^+\pi^+$	30
	ACCMOR	1989	$\pi^-(K^-)$ Cu 230 GeV	6
	E400	1987	$nA \sim 600$ GeV	102
	Biagi *et al.*	1985	Hyperon beam	53
Ξ_c^0	E687	1993	γ Be, $\Xi_c^0 \to \Xi^-\pi^+$	42
	ACCMOR	1990	$\pi^-(K^-)$ Cu 230 GeV	4
Ω_c^0	E687	1995	γ Be, $\Omega_c^0 \to \Sigma^+ K^- K^-\pi^+$	43
	WA89	1995	Σ^- Cu-C (expected soon)	

Table III: Lifetimes of the D^+, D^0, D_s^+ (ps).

	E687	PDG94	Accuracy (E687)	Accuracy (PDG94)
D^+	$1.048 \pm 0.015 \pm 0.011$	1.057 ± 0.015	1.8%	1.4%
D^0	$0.413 \pm 0.004 \pm 0.003$	0.415 ± 0.004	1.2%	1.0%
D_s^+	$0.475 \pm 0.020 \pm 0.007$	0.467 ± 0.017	4.5%	3.6%

and compared with the E687 final results, fractional errors are also quoted. The ratio between D^+ and D^0 lifetimes is thus known to within 1.7% and the ratio

Table IV: Lifetimes of the Λ_c^+, Ξ_c^0, Ξ_c^+, Ω_c^0 (ps).

	E687	PDG94	Accuracy (E687)	Accuracy (PDG94)
Λ_c^+	$0.215 \pm 0.016 \pm 0.008$	$0.200\ ^{+0.011}_{-0.010}$	8.3%	5.5%
Ξ_c^0	$0.101\ ^{+0.025}_{-0.017} \pm 0.005$	$0.098\ ^{+0.023}_{-0.015}$	25.2%	23.4%
Ξ_c^+	$0.41\ ^{+0.11}_{-0.08} \pm 0.02$	$0.35\ ^{+0.07}_{-0.04}$	27.2%	20.0%
Ω_c^0	$0.089\ ^{+0.027}_{-0.020} \pm 0.028$		43.7%	

between D_s^+ and D^0 lifetimes with 3.7% accuracy:

$$\frac{\tau(D^+)}{\tau(D^0)} = 2.547 \pm 0.043, \qquad \frac{\tau(D_s^+)}{\tau(D^0)} = 1.125 \pm 0.042 \ .$$

The lifetime ratios between baryons can also be extracted:

$$\frac{\tau(\Xi_c^+)}{\tau(\Lambda_c^+)} = 1.75 \pm 0.36, \qquad \frac{\tau(\Xi_c^0)}{\tau(\Lambda_c^+)} = 0.49 \pm 0.12 \ .$$

Since PDG94 a new measurement of $\tau(\Xi_c^+)$ by WA89 has been made available: $\tau(\Xi_c^+) = 0.32 \, ^{+0.08}_{-0.06} \pm 0.05$ ps, in very good agreement with the world average.

The first measurement of the Ω_c^0 lifetime

Among the baryons, the most important experimental result is the first measurement of the Ω_c^0 lifetime, performed by the E687 collaboration in the channel $\Omega_c^0 \rightarrow \Sigma^+ K^- K^- \pi^+$; evidence of this decay and details of the relative analysis have already been published by E687 [7]. The raw proper-time distribution in Fig. 1a indicates that the lifetime is quite short, comparable to the spectrometer
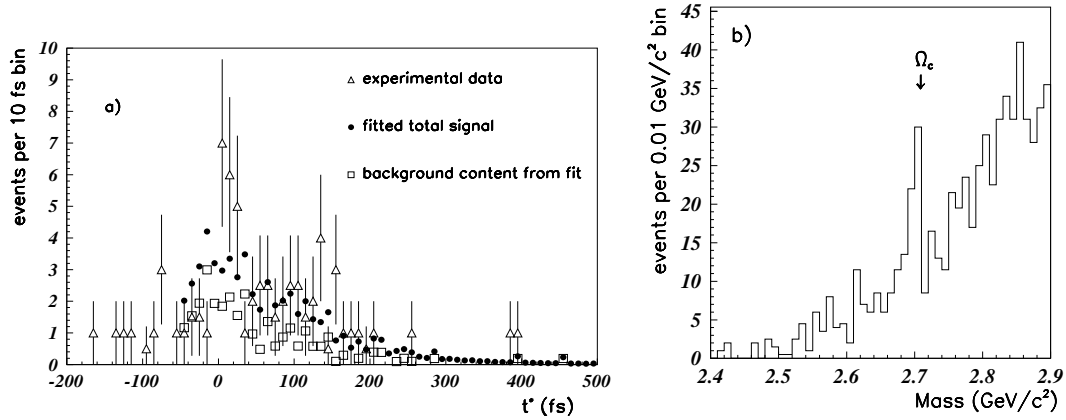

Figure 1: a) Proper-time evolution and b) mass distribution of the Ω_c^0 events.

time resolution, which is predicted by Monte Carlo to be $\sim 0.070 - 0.080$ ps.

To successfully measure this short lifetime, very accurate account of proper-time distribution smearing due to finite vertex resolution is necessary. Since smearing will cause some true signal events to appear to have negative proper-time, such events have to be included in the fit. To study the stability of the fit, to begin with all the events are fitted and then only those with proper time greater than a cut value, t^*_{cut}. To quote the final lifetime value, the collaboration adopts a $t^*_{\mathrm{cut}} > -0.050$ ps, as a compromise between a good signal-to-noise ratio and the largest possible statistics. The chosen sample also gives the best fit probability based on the Kolmogorov-Smirnov test.

Fig. 1b shows the mass distribution of events considered in the final fit. The results of the fits to all events and to events with proper times greater than a cut value, defined as t^*_{cut}, are shown in Fig. 2; within the statistical errors returned by the fit, all the fitted lifetime values are consistent. The large relative

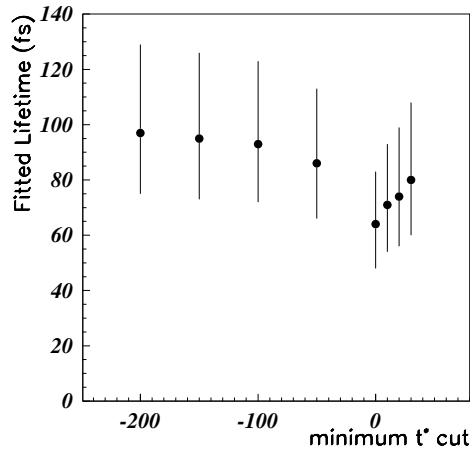Figure 2: Lifetime of the Ω^0_c for different minimum t^* cuts.

variation of the fitted lifetimes obtained by using different t^*_{cut} values indicates a possible systematic uncertainty, for which an upper limit of 0.0129 ps is estimated. Additional systematic contributions may come from the sideband locations, background lifetime, Monte Carlo simulation uncertainty and absorption of secondaries. All these effects are estimated and a final value for the Ω^0_c lifetime is quoted as

$$\tau(\Omega^0_c) = 0.089\,^{+0.027}_{-0.020}\,(\mathrm{stat.}) \pm 0.028\,(\mathrm{syst.})\ \mathrm{ps}.$$

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This result establishes the first measured full lifetime-hierarchy pattern:

$$\tau(\Omega_c^0) \leq \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+) < \tau(D^0) < \tau(D_s^+) < \tau(D^+).$$

4 Conclusions

The charmed-hadron lifetime field is now rather mature; in the meson sector the measurements are very precise (1–2%) and evidence for $\tau(D_s^+) > \tau(D^0)$ is provided at the 3σ level. These results pose severe new constraints on theoretical models describing charm decay, their precision probably exceeding the ability to compute them. In the baryon sector a significant improvement over previous Λ_c^+, Ξ_c^+ and Ξ_c^0 lifetime measurements has been reached in the last two years. The first measurement of the Ω_c^0 lifetime has also been performed by E687, making available a full lifetime-hierarchy pattern. More data on baryons are certainly needed and the continuous experimental effort to deal with $\tau \leq 10^{-13}$ s is worthwhile. Progress from E687/E831, WA89 and EXCHARM is expected soon.

On the theory side, efforts to develop systematic and self-consistent theoretical treatments of the inclusive weak decays of Heavy Flavour hadrons have been made. Hopefully, the cooperation between different *second generation technology* analyses (QCD sum rules, HQET, $1/m_Q$ expansion, lattice QCD *etc.*) will be fruitful. Charm lifetime studies are providing very useful information on perturbative and non-perturbative QCD effects, necessary to understand the phenomenology of the lightest of the heavy quarks; results on the charm family may therefore be important for predictions in the beauty sector and, hopefully, help illuminate the light quark world.

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